



U.S. AIR FORCE



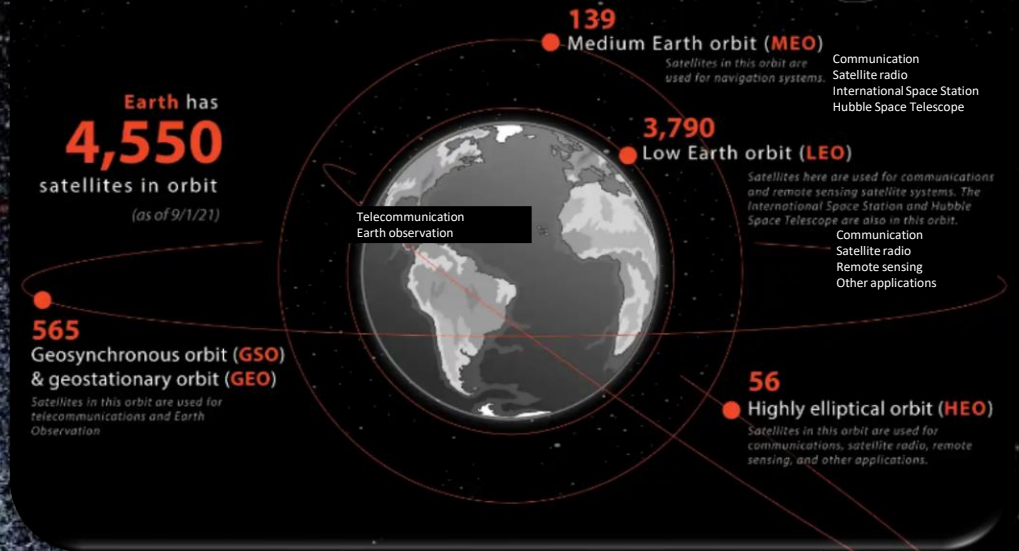
AFRL

SPACE-BASED POSITION, NAVIGATION AND TIMING RESEARCH

May 2024

USE OF SPACE IS GROWING EXPONENTIALLY

EVERY SATELLITE ORBITING EARTH AND WHO OWNS THEM



THE COUNTRIES WITH THE MOST SATELLITES



Total Number of Satellites

1	USA	2,804
2	China	467
3	United Kingdom	349
4	Russia	168
5	Japan	93
6	India	61
7	Canada	57
8	Germany	47
9	Luxembourg	40
10	Argentina	34
11	France	31
12	Spain	24
13	Italy	21
14	Israel	19
15	South Korea	18
16	Brazil	16
16	Netherlands	16
18	Finland	15
19	Australia	14
20	Saudi Arabia	13
20	Taiwan	13
20	United Arab Emirates	13
20	Switzerland	13
24	Singapore	11
25	Turkey	9
26	Indonesia	8
26	Norway	8
26	Mexico	8
29	Thailand	7
30	Kazakhstan	6

Countries With **5 Satellites**: Algeria, Belgium, Greece, and Sweden

Countries With **4 Satellites**: Denmark, Egypt, Malaysia, and Vietnam

Countries With **3 Satellites**: Czechia, Morocco, Nigeria, Pakistan, and South Africa

Countries With **2 Satellites**: Azerbaijan, Belarus, Ethiopia, Lithuania, Slovenia, and Venezuela

Countries With **1 Satellite**: Austria, Bangladesh, Bolivia, Bulgaria, Chile, Colombia, Ecuador, Estonia, Hungary, Iran, Iraq, Jordan, Kuwait, Laos, Mauritius, Monaco, Nepal, New Zealand, Paraguay, Peru, Qatar, Sri Lanka, Sudan, Tunisia, Turkmenistan, and Ukraine

SOURCES:

<https://www.ucsusa.org/resources/satellite-database>

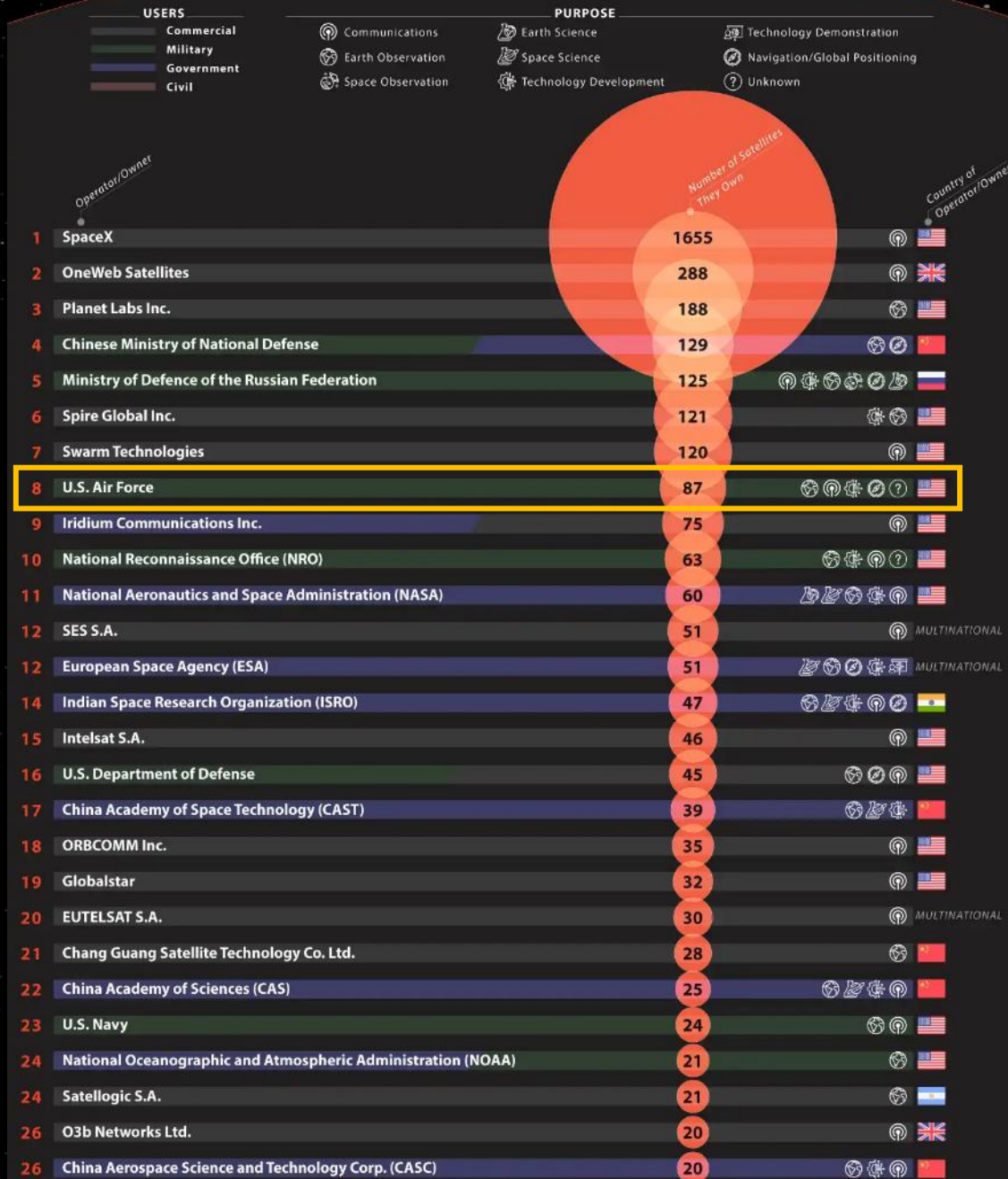
<https://maps.esri.com/rc/sat2/index.html>

<https://www.spacefoundation.org/space-brief/types-of-orbits/>



DEWESoft®

THE 50 OPERATOR/OWNERS of the Most Satellites Orbiting Earth



USERS

- Commercial
- Military
- Government
- Civil

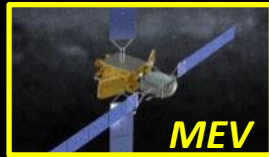
PURPOSE

- Communications
- Earth Observation
- Space Observation
- Earth Science
- Space Science
- Technology Development
- Technology Demonstration
- Navigation/Global Positioning
- Unknown

21st Century Space

Economic and national interests create new challenges

SPACEX
x12,000
amazon
x3200



India tests anti-satellite weapon

-Space News, 2019

Russian and US satellites collide

-BBC 2009

PNT in XGEO space is a challenge



1969	Today	2030+
~1500 objects	~10 ⁴ objects; human-operated	~10 ⁶ objects, autonomous
GEO, Lunar, Keplerian	GEO, Keplerian	Cis-lunar, non-Keplerian
~7 nations in space	~90 nations; commercial	?? nations, commercial; non-state



Space is vital to US economic and national security



The USSF Is Dedicated To Accessing, Protecting & Defending the Space Domain

VITAL TO OUR WAY OF LIFE



The U.S. Harnesses The Benefits Of Space Everyday For Communications, Global Markets, Weather, Scientific Exploration And More

The Global Space Economy Continues To Grow From \$450 Billion To An Estimated \$1 Trillion By 2040

VITAL TO MODERN WAY OF WAR



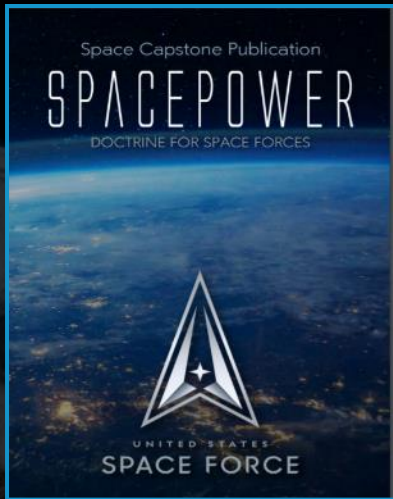
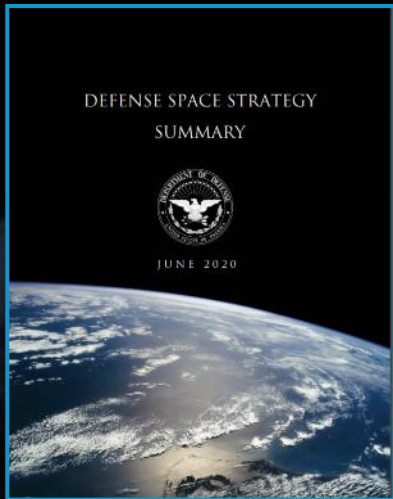
Potential Adversaries Have Recognized The U.S. Military's Dependence On Space And The Advantages Space Provides, And Are Developing Their Own Space Capabilities

In A Conflict, They Intend To Degrade Our Space Capabilities To Reduce Our Military Effectiveness and Degrade Our American Way Of Life

US Must Remain THE Leader in Space: Freedom of Action & Being First

Freedom Of Action In Space Must No Longer Be Assumed, It Must Be Underpinned By Strength And Leadership

Changing Environment



DESIRED CONDITIONS:

The space domain is secure, stable, and accessible. The use of space by the United States and our allies and partners is underpinned by sustained, comprehensive U.S. military strength. The United States is able to leverage our use of space to generate, project, and employ power across all domains throughout the spectrum of conflict.

CENTRAL PROBLEM:

The U.S. defense space enterprise was not built for the current strategic environment. The intentions and advancements of potential adversaries in space are threatening the ability of the United States to deter aggression, to protect U.S. national interests, and to fight and win future conflicts.

SPACEPOWER:

The sum of a nation's capabilities to leverage space for diplomatic, information, military, and economic activities in peace or war in order to attain national objectives.

GPS Under Threat


GPS is a military enabler and key civil worldwide infrastructure
Increasingly, GPS faces serious competition and market pressure from Galileo and Beidou

FORBES > BUSINESS > AEROSPACE & DEFENSE

GPS Spoofing in the Middle East Is Now Capturing Avionics

Eric Tegler Contributor

Dec 5, 2023, 09:15am EST



Avionics like those equipping Bombardier's Global 7500 business jet and other commercial aircraft ... BOMBARDIER

"What we've seen since late September," University of Texas researchers say, "is unprecedented. We have never seen commercial aircraft captured by GPS spoofing before."

Business and commercial aircraft are being led astray thanks to their sensor-fused navigation systems. A series of [spoofing incidents](#) beginning in late September has caused complete aircraft navigational system failures in some airliners and business jets overflying the Iraq- Iran area. As a result, one bizjet almost strayed into Iranian airspace without clearance.

Russian jammer in Syria seen interfering with flights to Israel — report

Pilot says spoofing, which tricks plane's GPS into thinking its somewhere else, affecting civilian flights over Mediterranean; Israel complained publicly of issue in 2019

By JOSHUA DAVIDOVICH
11 January 2022, 2:47 pm



China / Diplomacy

China's BeiDou and Russian GLONASS sign new deal to rival America's GPS satellite navigation

- Latest satellite navigation systems deal among 16 signed as Vladimir Putin met Xi Jinping in Beijing
- Agreement promises to ensure 'complementarity of the global navigation satellite systems in terms of system timescales', in a step up from a 2018 deal

Liu Zhen in Beijing
Published: 3:00pm, 5 Feb, 2022



China completes GPS rival Beidou with latest satellite launch

Beijing's decoupling from US moves forward in space ahead of Mars probe



The final satellite in the Beidou system was put into orbit on Tuesday from the Xichang Satellite Launch Center. (Photo courtesy of BeiDou Navigation Satellite System)

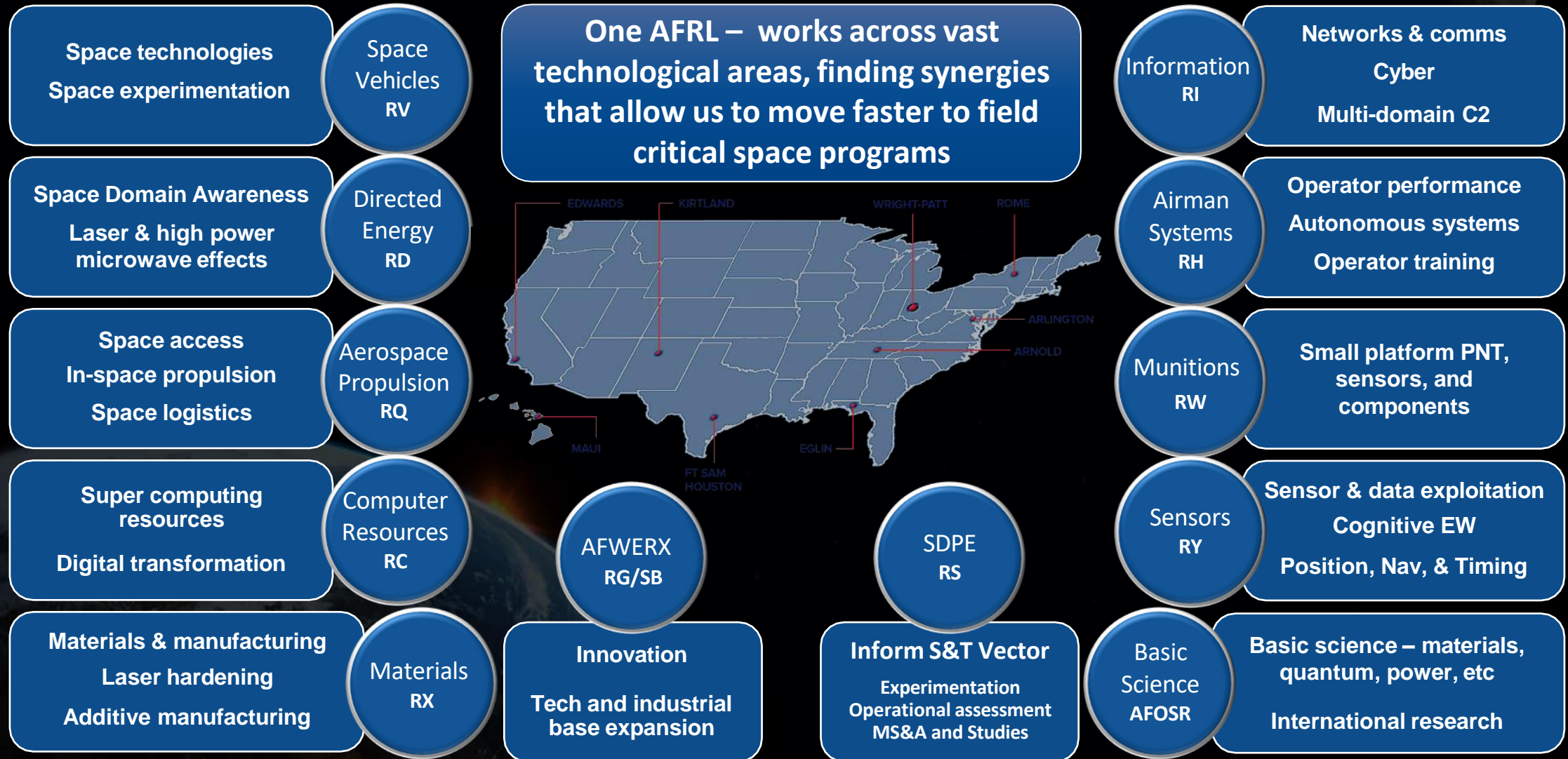
SHUNSUKE TABETA, Nikkei staff writer
June 23, 2020 23:58 JST

BELJING -- China has completed Beidou, its answer to the Global Positioning System of satellites used to navigate everything from cars to bombs, advancing Beijing's effort to cut its reliance on American technology.

GPS is subject to loss of trust through jamming and spoofing

US policy emphasizes robust and resilient, diversified PNT sources to ensure warfighter success

AFRL'S EXPANSIVE SPACE PORTFOLIO



Space Architecture Evolution

Today Stovepipe Missions Areas 0-5 yrs



Attributes

- Stovepiped acquisition and ops
- Strategic requirements focused
- Lengthy requirements process
- Large, costly programs
- Incremental technology
- Limited resiliency

Midterm Hybrid Architecture 5-15 yrs



Attributes

- Mixture of strategic and tactical
- Orbital regime diversification
- Platform size variation
- International, commercial and DoD coordination and integration
- Multi-path communication

Far term Heterogeneous Architecture 15-30 yrs



Attributes

- Resembles more of the modern-day internet – IoT of Space
- Ubiquitous communication
- Integrated autonomy and ML/AI
- Truly integrated multi-domain
- Ubiquitous information exploitation and decision making

Positioning, Navigation and Timing

How to Ensure PNT Services in Contested Environments?

- GPS augmentation
- Multi-GNSS
- Anti-jam
- Anti-spoof

Rapidly Converging on Validated, Fieldable Solutions

- Laboratory testing
- Field testing
- Independent evaluation

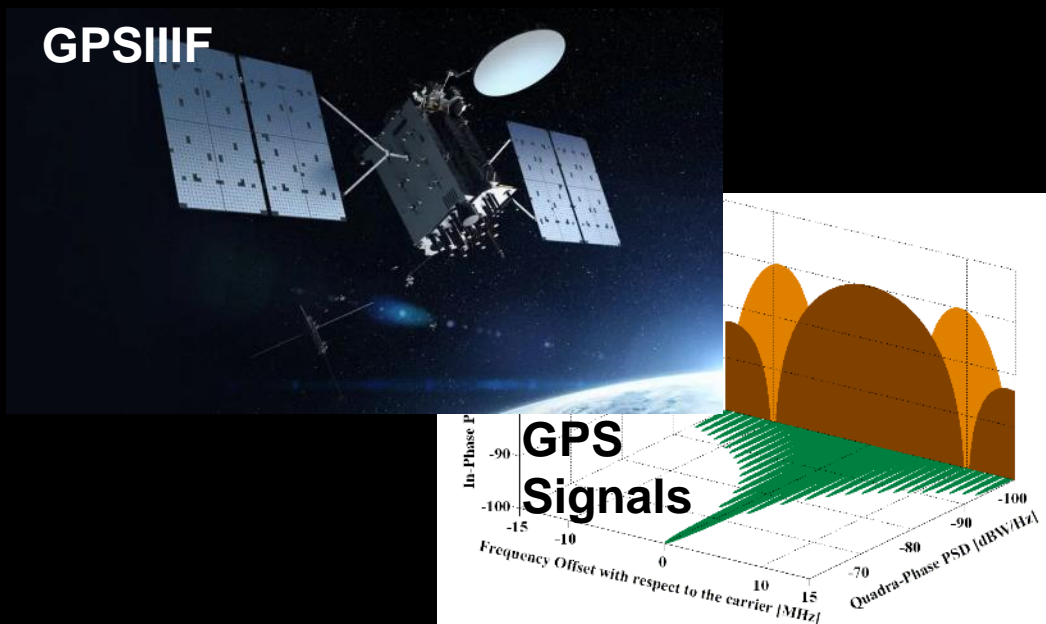
Modeling and Simulation to Quantify Net Gains

- Performance models validated through testing
- System of systems quantification
- Feed results back into force design analytics
- Feed insights forward into acquisition and ops



AFRL Technologies at the Forefront of Resilient PNT

Year 2035: Projected M-Code full force deployment. RMP plus M-Code plus CRPA address threat anticipated in the early 2000s



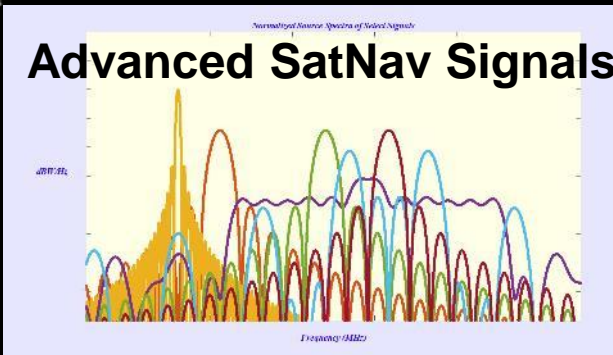
NTS-3



Quantum INS



Advanced SatNav Signals



Year 2035+: The *Emerging* threat, as well as specialized user needs, challenges us to continue to improve and adapt our approach.

SatNav Reprogrammability (e.g. NTS-3) + Advanced Signals (e.g. Q-CODEs) + Agile Receivers (e.g. SDUE) + Accurate Relative Navigation (e.g. Quantum-INS, Optical Clocks & Precise Time Transfer) = **Resilient PNT**

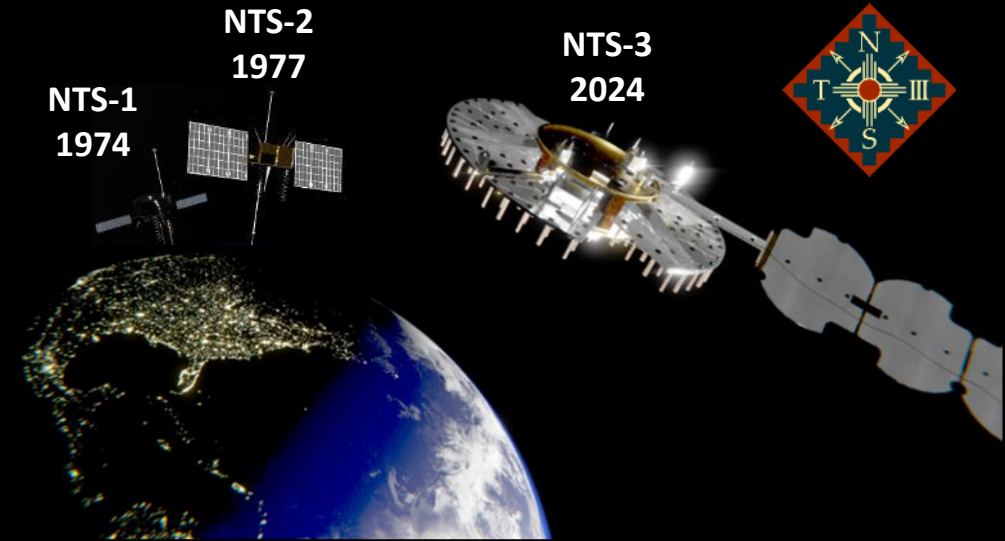
NTS-3=Navigation Technology Satellite-3

Q-CODE=Quantum-enabled Cognitive, Operationally Responsive, Dispersive, Enhanced Signals

SDUE=Software Defined User Equipment (an AFLCMC program, not discussed in this briefing)

Navigation Technology Satellite -3 (NTS-3) Space Vanguard

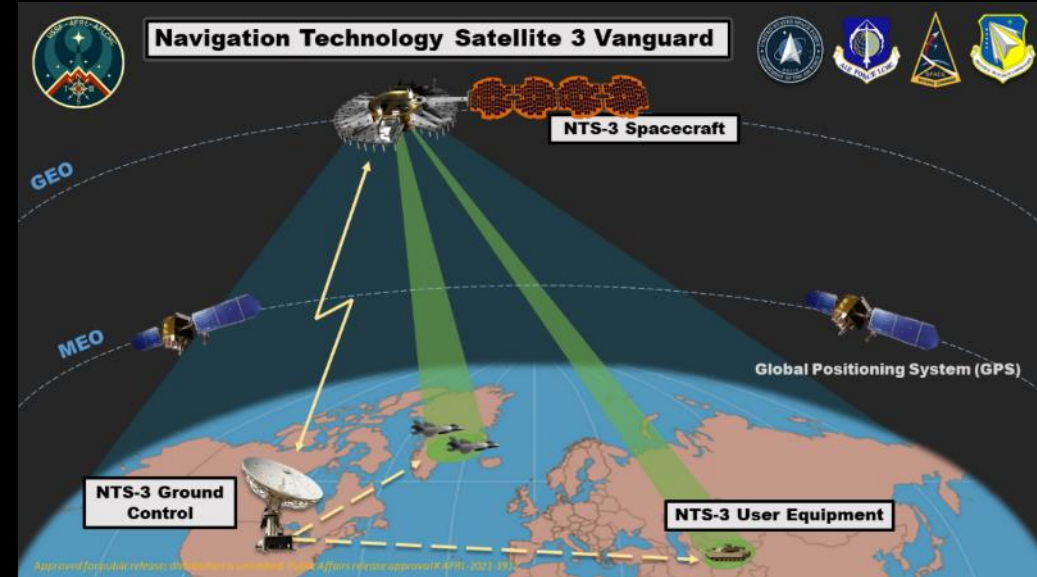
- Two satellite navigation experiments were launched by the United States in the 1970s
 - NTS-2 was followed by 40+ years of GPS
 - NTS-3 will be the first US DoD experimental navigation satellite in 45 years
- New Technologies being tested
 - Reprogrammable signals
 - Reprogrammable receivers – user equipment
 - Flexible timekeeping – improved time
 - Advanced electronically scanned array antennas
 - Responsive ground control



NTS-3 will test on-orbit reprogrammability, enabling broadcast of new signals to improve performance by avoiding and defeating interference and adding signatures to counter spoofing

Navigation Technology Satellite -3 (NTS-3)

- Developing advanced techniques and technologies to detect and mitigate interference to PNT capabilities
- Increase system resiliency for military, civilian and commercial users
- NTS-3 will operate in GEO and will identify key aspects for new GPS receivers that incorporate multiple signals and readily adapt to warfighter needs
- Prototype will involve space-based test vehicle, ground based C2 and agile software defined radios for the user
- NTS-3 will test a new digital signal generator that can be reprogrammed on-orbit, enabling it to broadcast new signals, improve performance by avoiding and defeating interference, and adding signatures to counter spoofing



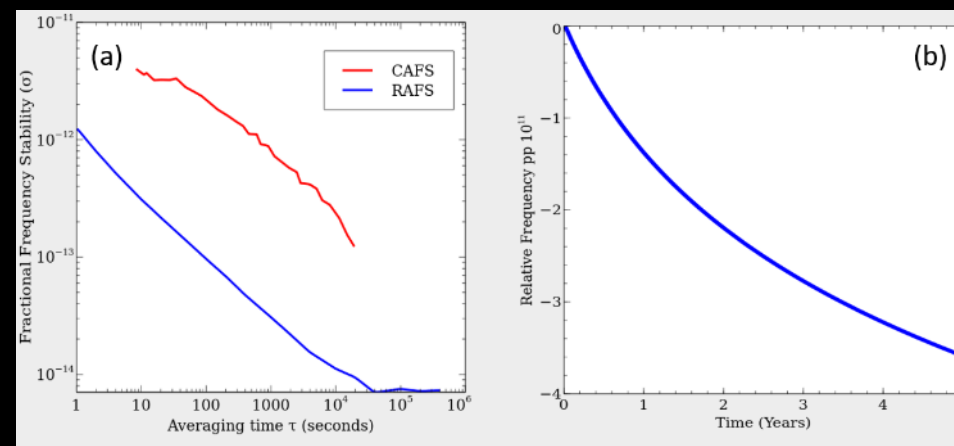
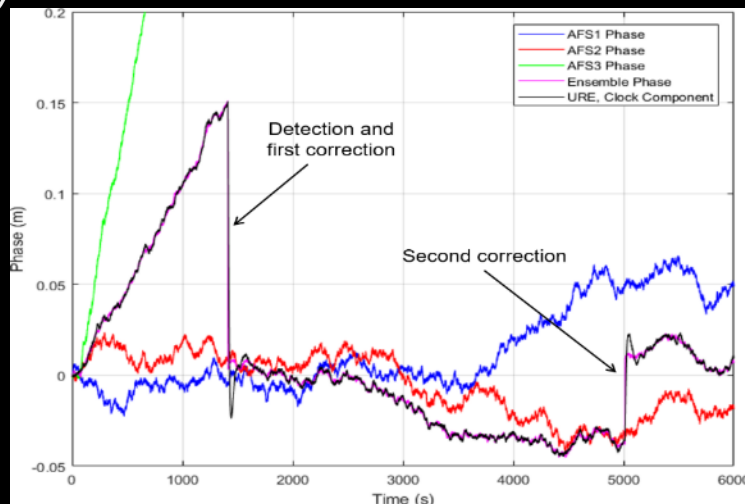
Reprogrammable Receivers

- Reprogrammability must be enterprise-wide (space, ground control, and user segments)
- NTS-3 leverages recent advances in software-defined radios (SDRs), and specifically MITRE's GNSS Test Architecture (GNSSTA) to receive new signals
- Flexibility includes:
 - Modulations
 - Power
 - Multiplexing methods
 - Data framing
 - Data content



Technologies: Flexible Timekeeping

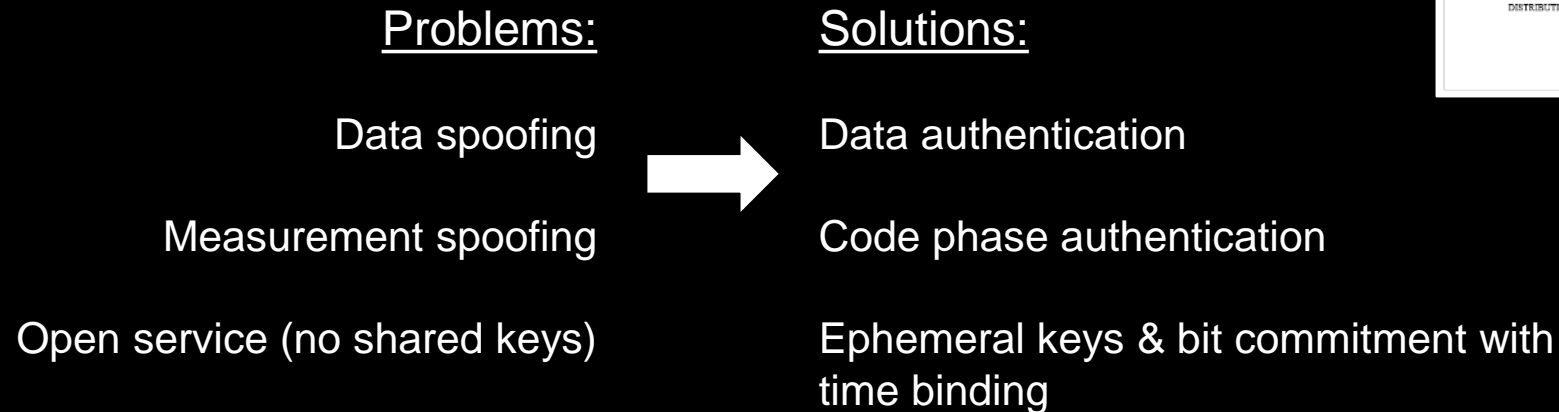
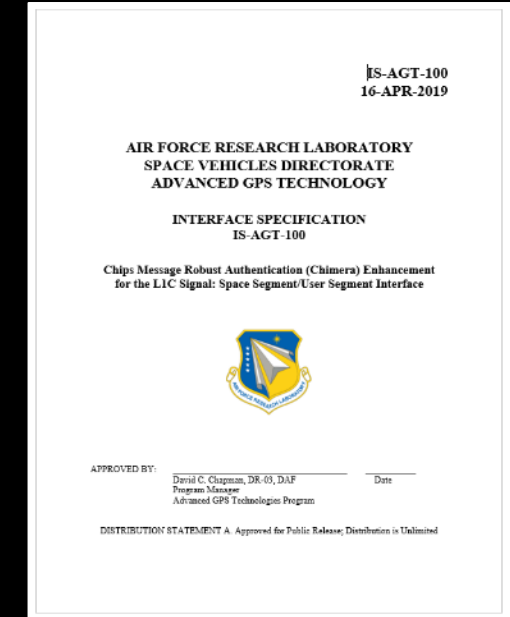
- Onboard clocks are
 - Rubidium atomic frequency standard (RAFS)
 - Cesium atomic frequency standard (CAFS)
 - Voltage-controlled crystal oscillator (VCXO)
- Use high-rate 12-bit telemetry to characterize clock behavior (nominal vs. eclipse, maneuvers, etc.)



- Optimally combine all available clocks into an onboard ensemble
- Automatically detect anomalies (phase or frequency breaks), attribute to a specific clock, and correct the timescale
- Experiment with ability to discipline VCXO using a ground-based clock

Signal Authentication: Chimera Overview

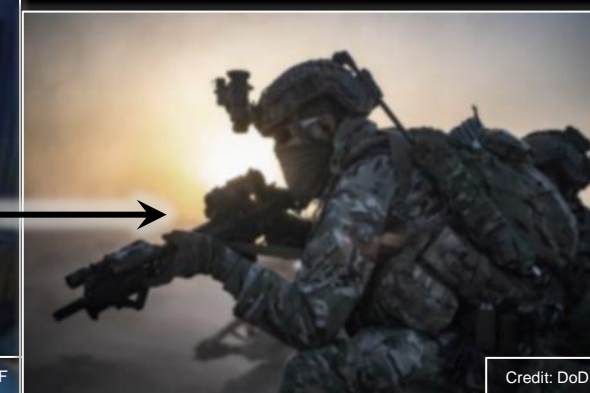
- Signal enhancement that jointly authenticates both navigation data messages and the spreading code on an L1C signal
 - Specified in IS-AGT-100
- Two concurrent flavors
 - Slow channel Chimera is self-contained in the signal and uses a public key
 - Fast channel Chimera uses an out-of-band source of ephemeral fast channel keys



Chimera = Data authentication + code phase authentication + time binding

Responsive Ground Control

- Implements reprogrammability and coordination across all segments
- Increased automation & autonomy
- Incorporates commercial command & control sites as needed



Lightweight Military Satnav

- Low SWAP-C alternative to M-code MGUE
 - NOT an M-code replacement
- Target users
 - Military “Internet of Things”
 - Cost and power draw are priorities
 - Vulnerable and underserved equipment

Characteristics/Goals

- Low power signal design (chip rate/bandwidth)
- Alternative security design, including cryptographic algorithm, key distribution method, and receiver information security
- Commercial chipsets, custom ASICs, SDRs, and Government-owned firmware
- Commercial security processes and standards
- Contested performance: Open signals and M-code
- Constellation agnostic – LEO (SDA), MEO, GEO sats

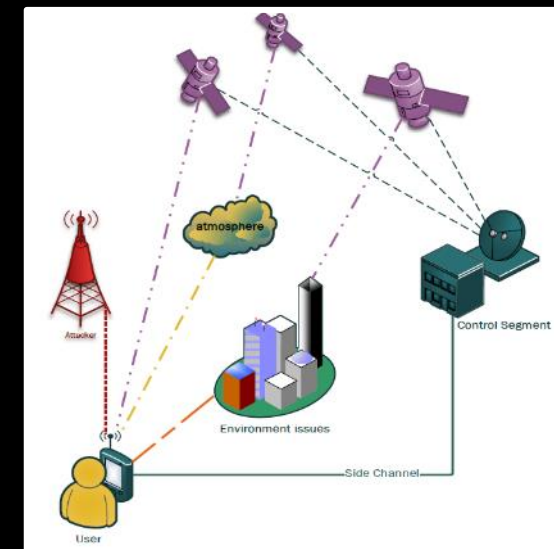


- Dismounted soldiers
- Unattended sensors, sonobuoys
- Small UAVs
- Wearables
- Tactical radios/smartphones

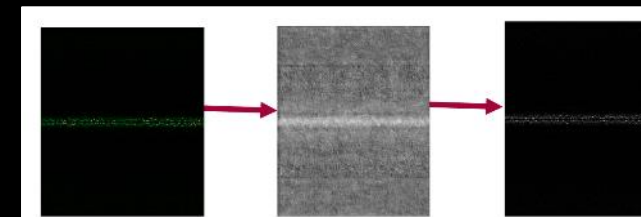


Machine Learning for PNT Resilience

- Adversarial PNT attacks (jamming, spoofing) are becoming more common
- Project Goal: Use AI/ML methods to close the PNT OODA loop rapidly
- Challenge: Lack of contested environments datasets
- Portable Intelligence Gathering Experimental Observation Node (PIGEON) – edge node sensor
 - ID, classify, recommend PNT COA
 - Variational Autoencoder - 95% I/Q data size reduction w/out performance loss
- Machine Learning Toolset O/S (MLTos)
 - Provides ground truth datasets & tools for testing and evaluating models
- PIGEON & MLTos h/w and s/w developed are Gov't IP
 - Distributable under Distro-D (DOD/DOD Contractors)



PNT OODA Loop



Data Size Reduction via VAE



PIGEON



MLTos (laptop)

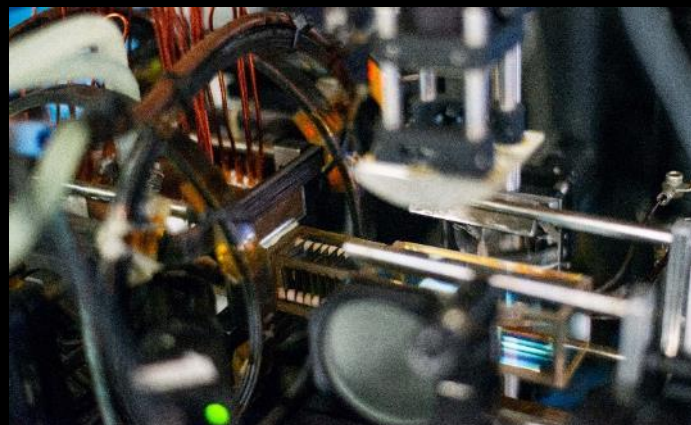
Quantum PNT

Quantum Sensing

In-house: Quantum Accelerometer with Enhanced Dynamic Range (QuAc-ER), Nanoparticles accel & VLF sensor

Contract: Gyros

Collab: Other DoD, Int'l, Academia



Quantum Timing

In-house: Optical Rubidium Atomic Frequency Standard (ORAFS), Optical Time Transfer

Contract: SBIRs

Collab: Other DoD, NIST

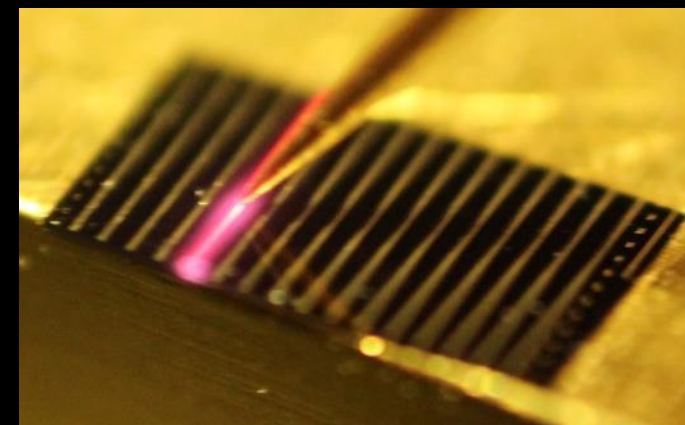


Quantum Components & Materials

In-house: Microcombs, all-fiber lasers, alkali sources, control systems, atom chips, cavities

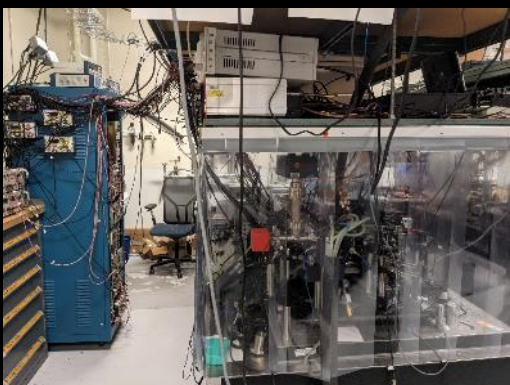
Contract: Narrow linewidth lasers, PICs

Collab: Sandia, Other DoD, NIST, MITLL, Academia, Int'l



Crawl, Walk, Run Quantum Technologies to Space

Accelerating the Quantum Sensing & Timing technologies out of the lab!



Lab System



QuAc-ER "ready" for tests out of lab



R/V Point Sur



Working hard or hardly working(?) at sea

1st (?) ever field test for trapped atom inertial sensor

Tested all subsystems/components at sea

- Lasers locking worked very well
- Too much impact on polarization from temperature
- Most everything else worked well



Operating through the night

